

# Strangeness in the Nucleon

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## Abstract.

There are several different experimental indications, such as the  $\sigma_{\pi N}$  term, strange spin polarization, strangeness contribution to the magnetic moment of the proton, ratio of strange and non strange quark flavor distributions which suggest that the nucleon contains a hidden strangeness component which is contradictory to the naive constituent quark model. Chiral constituent quark model with configuration mixing ( $\chi\text{CQM}_{\text{config}}$ ) is known to provide a satisfactory explanation of the “proton spin problem” and related issues. In the present work, we have extended the model to carry out the calculations for the parameters pertaining to the strange quark content of the nucleon, for example, the strange spin polarization  $\Delta s$ , strange components of the weak axial vector form factors  $\Delta\Sigma$  and  $\Delta_8$  as well as  $F$  and  $D$ , strangeness magnetic moment of the proton  $\mu_p^s$ , the strange quark content in the nucleon  $f_s$  coming from the  $\sigma_{\pi N}$  term, the ratios between strange and non-strange quarks  $\frac{2s}{u+d}$  and  $\frac{2s}{\bar{u}+\bar{d}}$ , contribution of strangeness to angular momentum sum rule etc.. Our result demonstrates the broad consistency with the experimental observations as well as other theoretical considerations.

**Keywords:** Chiral constituent quark model, proton spin problem

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There is currently enormous interest in the determination of the strangeness content of the nucleon. It is crucial to our understanding of Quantum Chromodynamics (QCD) in the confining regime and to determine precisely the role played by non-valence quark flavors in understanding the internal structure of the nucleon. Theoretically, strange quarks are interesting because they do not appear explicitly in most quark model descriptions of the nucleon. The naive constituent quark model [1] provides a useful intuitive picture of the nucleon substructure and has seen considerable success in accounting for a wide range of properties of the low-lying hadrons, however one knows that there is more to the nucleon than the three constituent quarks. A clear indication in this regard was provided by the EMC measurements of polarized structure functions of proton in the deep inelastic scattering (DIS) experiments [2, 3], indicating that the valence quarks of the proton carry only about 30% of its spin which includes the contribution even of the strange quark polarization. Several interesting facts have also been revealed regarding the quark distribution functions in the DIS experiments [4, 5, 6, 7] and there are fairly strong signals indicating that the flavor structure of the nucleon is not limited to  $u$  and  $d$  quarks only.

Apart from the indications of DIS data regarding  $\Delta s$  [3] explaining the violation of Ellis Jafe sum rule, this point is further illustrated by the phenomenological results of the pion-nucleon sigma term ( $\sigma_{\pi N}$ ) [8] which is extracted from the  $\pi N$  scattering data and is a measure of explicit chiral symmetry breaking in QCD. It gives a strong indication regarding the strange quark content of proton defined as  $f_s = \frac{s+s}{\Sigma(\bar{q}+q)}$ . The OZI

rule would imply  $f_s = 0$  [9]. However, the observed result for  $\sigma_{\pi N}$  indicates that the strange flavor is also present in the nucleon. Recently, there has been a considerable interest in calculating the strangeness contribution to the magnetic moment of the proton  $\mu_p^s$  as the same has been measured in the experiments performed with parity violating elastic electron-proton scattering at JLab (HAPPEX) [10] and MIT-Bates (SAMPLE) [11]. Similarly, DIS experiments have given fairly good deal of information regarding the other relevant observables related to the strange quark content of the nucleon, for example, the ratios between strange and non-strange quarks  $\frac{2s}{u+d}$  and  $\frac{2s}{\bar{u}+\bar{d}}$  as measured by the CCFR Collaboration in their neutrino charm production experiments [12].

The chiral constituent quark model ( $\chi$ CQM), as formulated by Manohar and Georgi and later developed by Eichten *et al.* [13], can yield an adequate description of the observed proton flavor and spin structure which is puzzling from the point of view of naive constituent quark model [9]. Further, chiral constituent quark model with configuration mixing ( $\chi$ CQM<sub>config</sub>) is known to improve the predictions of  $\chi$ CQM [14]. The key to understand the “proton spin problem”, in the  $\chi$ CQM formalism [9], is the fluctuation process  $q^\pm \rightarrow \text{GB} + q'^\mp \rightarrow (q\bar{q}') + q'^\mp$ , where GB represents the Goldstone boson and  $q\bar{q}' + q'$  constitute the “quark sea” [9, 14, 15]. The effective Lagrangian describing interaction between quarks and a nonet of GBs, consisting of octet and a singlet, can be expressed as  $\mathcal{L} = g_8 \bar{\mathbf{q}} \Phi \mathbf{q} + g_1 \bar{\mathbf{q}} \frac{\eta'}{\sqrt{3}} \mathbf{q} = g_8 \bar{\mathbf{q}} \left( \Phi + \zeta \frac{\eta'}{\sqrt{3}} I \right) \mathbf{q} = g_8 \bar{\mathbf{q}} (\Phi') \mathbf{q}$ , where  $\zeta = g_1/g_8$ ,  $g_1$  and  $g_8$  are the coupling constants for the singlet and octet GBs, respectively,  $I$  is the  $3 \times 3$  identity matrix. The GB field  $\Phi'$  includes the octet and the singlet GBs. The parameter  $a (= |g_8|^2)$  denotes the probability of chiral fluctuation  $u(d) \rightarrow d(u) + \pi^{+(-)}$ , whereas  $\alpha^2 a$ ,  $\beta^2 a$  and  $\zeta^2 a$  respectively denote the probabilities of fluctuations  $u(d) \rightarrow s + K^{-(0)}$ ,  $u(d, s) \rightarrow u(d, s) + \eta$ , and  $u(d, s) \rightarrow u(d, s) + \eta'$ .

It would be interesting to mention here that the presence of  $s\bar{s}$  is not suppressed by the basic mechanism that generates quark sea. Contribution of the strange quark to the nucleon spin is one of the major interests in connection with the “Proton Spin Problem”. It is crucial to our understanding of QCD in the confining regime and gives a direct insight to determine precisely the role played by heavier, non-valence flavors in understanding the nucleon internal structure. Almost no information exists, however, regarding the low-energy manifestations of the sea. Therefore, it would be interesting to extend the  $\chi$ CQM<sub>config</sub> for the calculation of parameters pertaining to the strangeness content of the nucleon. In particular, we would like to calculate the strange spin polarization  $\Delta s$ , strange components of the weak axial vector form factors  $\Delta \Sigma$  and  $\Delta_8$  as well as  $F$  and  $D$ , strangeness magnetic moment of the proton  $\mu_p^s$ , the strange quark content in the nucleon  $f_s$  coming from the  $\sigma_{\pi N}$  term, the ratios between strange and non-strange quarks  $\frac{2s}{u+d}$  and  $\frac{2s}{\bar{u}+\bar{d}}$ , contribution of strangeness to angular momentum sum rule and the contribution of gluon polarization in sea. Further, it would also be interesting to carry out a detailed analysis for the role of SU(3) symmetry breaking and the strangeness parameters.

To study the role of the strange quarks in the nucleon, one needs to formulate the experimentally measurable quantities having implications in this model. The spin structure of a nucleon is defined as [9, 14, 15]  $\hat{B} \equiv \langle B | N | B \rangle$ , where  $|B\rangle$  is the nucleon wavefunction and  $N$  is the number operator giving the number of  $q^\pm$  quarks. The contribution to the proton spin in  $\chi$ CQM<sub>config</sub> is given by the spin polarizations defined as  $\Delta q = q^+ - q^-$ .

After formulating the spin polarizations of various quarks, we consider several measured quantities which are expressed in terms of the above mentioned spin polarization functions. The strangeness contribution to the flavor non-singlet components  $\Delta_3^s$  and  $\Delta_8^s$ , usually calculated in the  $\chi$ CQM, are obtained from the neutron  $\beta$ -decay and the weak decays of hyperons. The flavor non-singlet component  $\Delta_3$  is related to the well known Bjorken sum rule. Another quantity which is usually evaluated is the flavor singlet component  $\Delta\Sigma = \frac{1}{2}(\Delta u + \Delta d + \Delta s)$ , in the  $\Delta s = 0$  limit, this reduces to the Ellis-Jaffe sum rule. We have also considered the quark distribution functions which have implications for the strange quark content. For example, the antiquark flavor contents of the “quark sea”, the strange quark content in the nucleon  $f_s$ , the ratios between strange and non-strange quarks  $\frac{2s}{u+d}$  and  $\frac{2\bar{s}}{\bar{u}+\bar{d}}$ . Apart from the above mentioned spin polarization and quark distribution functions, we have also calculated the strangeness magnetic moment of the proton  $\mu_p^s$ .

In Table 1, we have presented the strangeness parameters incorporating spin dependent polarization functions along with the magnetic moments. As is evident from Table 1, the  $\chi$ CQM<sub>config</sub> is able to give a very good fit for  $\Delta s$  and  $\mu_p^s$ . It needs to be mentioned that the strangeness magnetic moment of the proton  $\mu_p^s$  is in good agreement with the HAPPEX data however it is significantly different when compared with the SAMPLE data, therefore the quality of numerical agreement can be assessed only after the data gets refined. It also needs to be mentioned that the strange quark contribution to the magnetic moment has been subject of intense experimental and theoretical considerations in the recent times. The present calculation not only agrees with some theoretical approaches but is also in agreement with most of the experimental results. Again, a refinement in the data would tell us about the extent to which the symmetry breaking values are required.

In Table 2, we have presented strange quark flavor distribution functions. Interestingly, the  $\chi$ CQM<sub>config</sub> is able to give excellent account of the measured values. The data has been obtained in the case of  $f_s, \frac{2s}{u+d}, \frac{2\bar{s}}{\bar{u}+\bar{d}}, \frac{f_3}{f_8}$  wherein we find an almost perfect agreement. Again, refinement of the data would not only test the  $\chi$ CQM<sub>config</sub> but also shed light on the mechanisms of  $\chi$ CQM<sub>config</sub>. Recently, there has been a lot of interest regarding the parameter  $f_s$ , which is related to  $\sigma_{\pi N}$  term obtained from low energy pion-nucleon scattering. An excellent agreement in the present case indicates the correct estimation of the role of sea quarks as has also been advocated by Scadron [16].

In conclusion, it would be interesting to mention that the success of  $\chi$ CQM<sub>config</sub> suggests that at leading order, the model envisages constituent quarks, the octet of Goldstone bosons ( $\pi, K, \eta$  mesons) and the *weakly* interacting gluons as appropriate degrees of freedom.

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**TABLE 1.** The calculated values of the strange spin distribution functions and related parameters.

Parameter	Data	NRQM	$\chi$ CQM	
			SU(3) symmetry	SU(3) symmetry breaking
$\Delta s$	$-0.07 \pm 0.04$ [3]	0	-0.14	-0.03
$\Delta_8^s$	$\Delta_8 = 0.58 \pm 0.025$ [17]	1	0.28	0.14
$\Delta \Sigma^s$	$\Delta \Sigma = 0.31 \pm 0.11$ [17]	1	0.14	0.07
$F^s$	$F = 0.462$ [17]	0.665	-0.025	-0.035
$D^s$	$D = 0.794$ [17]	1	0.025	0.035
$\mu_p^s$	$-0.038 \pm 0.042$ [10] $-0.36 \pm 0.20$ [11]	0	-0.06	-0.04

**TABLE 2.** The calculated values of the strange quark flavor distribution functions and related parameters.

Parameter	Data	NRQM	$\chi$ CQM	
			SU(3) symmetry	SU(3) symmetry breaking
$\bar{s}$	—	0	0.408	0.11
$\bar{u} - \bar{d}$	$-0.118 \pm 0.015$ [6]	0	-0.118	-0.118
$\bar{u}/\bar{d}$	$0.67 \pm 0.06$ [6]	—	0.68	0.68
$I_G$	$0.254 \pm 0.005$ [6]	0.33	0.254	0.254
$\frac{2\bar{s}}{\bar{u}+\bar{d}}$	$0.099^{+0.009}_{-0.006}$ [12]	0	0.236	0.09
$\frac{2\bar{s}}{\bar{u}+\bar{d}}$	$0.477^{+0.063}_{-0.053}$ [12]	0	1.78	0.48
$f_s$	$0.10 \pm 0.06$ [12]	0	0.18	0.09
$f_3/f_8$	$0.21 \pm 0.05$ [12]	0.33	0.23	0.21

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